# Applicability of 3D-dental reconstruction in cervical odontometrics

**(This paper has been accepted for publication in American Journal of Physical Anthropology)**

# Applicability of 3D-dental reconstruction in cervical odontometrics

**Seyedeh M. Kazzazi[a], Elena F. Kranioti[a b]**

[a]Edinburgh Unit for Forensic Anthropology, School of History Classics and Archaeology, University of Edinburgh, 4 Teviot Place, EH8 9AG, Edinburgh, UK.

[b]Department of Medical Imaging, University Hospital of Heraklion, Heraklion, Crete 71110, Greece.

## ABSTRACT

**Objectives:** The objective of this study was to assess the accuracy, reliability, and reproducibility of CT images in measuring cervical mesiodistal and buccolingual tooth sizes, by comparing the values obtained by 3D virtual models from CT images with those obtained using digital calipers.

**Materials and Methods:** In total, 530 maxillary and mandibular teeth of 51 individuals from two Iron Age sites were scanned using a Siemens Somatom sensation 64-slice Computed Tomography machine, and the images were reconstructed and measured. Values obtained by direct measurement served as the primary reference for cervical measurements. Intra- and inter-observer reliability was assessed by calculating technical error of measurements (TEM), relative technical error of measurements (rTEM), and the coefficient of reliability (R).

**Results:** Results showed that virtual cervical measurements were not significantly different from the actual measurements, and the correlation of the two measurement methods shows that the methods are comparable. Inter- and intra-observer error analysis also indicated high replicability of measurements with both measuring methods ($R > 0.99$). The rTEM values for all the measurements were below the 5% standards for anthropometric studies.

**Discussion:** Computed Tomography (CT) is a non-invasive technique that allows for an accurate and detailed visualization of morphological features without causing any damage to teeth. Our findings indicate that virtual odontometric analysis is a reliable method, similar to traditional physical odontometric analysis. Currently, the virtual system is likely to be more suitable for fragile specimens, such as archaeological samples.

## KEYWORDS

Dental cervical measurements, Computed Tomography, three-dimensional

## INTRODUCTION

Dental measurements are widely used in bioarchaeology and forensic anthropology for sex estimation, as teeth are extremely resistant to post-mortem damage and disintegration. Cervical mesiodistal and buccolingual measurements are among the most common types of tooth metric variables. These measurements, compared to traditional crown mesiodistal and buccolingual measurements, are far less affected by dental wear (Hillson et al., 2005), thus allowing a larger dataset to be obtained with a broader range of ages represented, particularly in archaeological samples, which are frequently subject to wear.

Measurement-related methods in sex assessment studies have usually involved hand-held calipers. Recently, however, advances in image analysis technologies, such as Computed Tomography (CT) scanning and virtual imaging techniques, have introduced new tools for collecting dental measurements. The advantages of calipers are that they are simple to use and portable, and the reasonable accuracy and reproducibility of manual measurements obtained from skeletal and dental remains have been confirmed by previous studies (Moorrees et al., 1957; Hunter & Priest, 1960). Nevertheless, in order to avoid the calipers damaging the samples, great care needs to be taken. Furthermore, it is possible to obtain only a limited number of linear measurements (Hunter & Priest, 1960; Richardson & Malhotra, 1975). Image analysis techniques provide also an accurate and reliable approach, allowing for more extensive examination. The advantages of this system over manual methods is that it is non-invasive and also permits researchers to obtain multiple measurements from a single image (McKeown et al., 2002). The accuracy of CT scans in crown and root length measurements have been evaluated in orthodontic studies (Kim et al., 2007; Liu et al., 2010; Tarazona et al., 2013).

The aims of this study were a) to assess the reliability, accuracy, and reproducibility of cervical mesiodistal and buccolingual measurements from virtual models created using CT scan images, and b) to compare them with the same measurements obtained using physical digital calipers on actual teeth. We used the digital calipers method as a standard, because the reliability and accuracy of this method has previously been tested (e.g. Viciano et al., 2015; Kazzazi & Kranioti, 2016).

## MATERIALS AND METHOD

Physical and virtual cervical mesiodistal and buccolingual measurements were taken from a total of 530 maxillary and mandibular teeth from 51 skeletons (30 males, 21 females) from Hasanlu and Dinkha Tepe collections, two Iron Age sites in north-western Iran (Dyson, 1983). The Hasanlu and Dinkha Tepe skeletons are stored in the University of Pennsylvania's Museum of Archaeology and Anthropology (Monge & McCarthy, 2011).

**Physical cervical measurements**

Direct cervical mesiodistal and buccolingual measurements were collected using Hillson-Fitzgerald dental calipers on actual teeth following the method outlined by Hillson et al. (2005). The caliper tips were placed on the surface of the enamel occlusal to the cement-enamel junction (CEJ).

**Virtual cervical measurements**

The same cervical mesiodistal and buccolingual measurements were taken of virtual models of each tooth separately. CT scans of maxillae and mandibles from the two collections were used to create virtual teeth models. The skulls were scanned at the Hospital of the University of Pennsylvania using a Siemens Somatom sensation 64-slice CT machine. Data were collected using a slice thickness of 0.5 mm and a matrix of 512 × 512 pixels. All data were saved in the Digital Imaging and Communications in Medicine (DICOM) format. The CT scans were obtained through the Open Research Scan Archive.

Virtual models of the teeth were reconstructed using manual segmentation in the Amira 6.01 software package. Two different threshold levels were used for tooth segmentation: one to segment the root from the jaw, one to segment the crown from the root. Root segmentation thresholds were calculated using the half maximum height protocol of Spoor et al. (1993) for each skull, and crown segmentation thresholds were set visually for each tooth. The latter segmentation helps the user to detect the CEJ line more accurately when placing cervical measurement landmarks: this is due to the difficulty of identifying the CEJ line on virtual models, compared to using actual teeth. As a result of visually adjusting the threshold parameters, different threshold levels were obtained for different teeth in the same DICOM data sets and between different data sets. Segmentation was performed in the axial view from crown to apex using the magic wand tool in AMIRA. Crown and root of each tooth were color-coded to facilitate differentiation. No smoothing functions were applied to the 3D tooth structure (Fig. 1). Liu et al. (2010) reported that smoothing function caused a reduction of the root volume measurement by 3-12%. For the cervical measurements, each tooth was rotated in 3D space to find the best possible view for determining the mesiodistal and buccolingual landmarks. All the 3D landmarks were placed on the surface of the enamel occlusal to the CEJ. The virtual measurement tools in AMIRA were then used. The virtual tool was preferred to the calliper because it measures from points directly on the model's surface, ensuring that the measurements accurately fit the surface of the crown/enamel.

Measurements were taken from the right maxillary and mandibular teeth, because the number of right teeth was considerably larger than the number of left teeth. Samples with dental caries, heavy calculus deposits, and hypoplastic defects along the CEJ were excluded, in order to avoid the possibility of incorrect measurements.

**Statistical Analysis**

To assess intra-observer error, cervical measurements were obtained by the author (SK) at different time points in 35 randomly selected individuals from the original sample. To evaluate inter-observer error, 30 randomly selected individuals were re-measured by a second observer (AH). Where present, both contralateral teeth were measured in the same individuals, with two weeks between the two measurements. Technical error of measurements (TEM), relative technical error of measurements (rTEM), and the coefficient of reliability (R) (Ulijaszek & Kerr, 1999) were used to determine the differences between the measurements.

All measurements were placed in an Excel spreadsheet and analyzed using the SPSS 21 software for Windows. All data were checked using the Kolmogorov-Smirnov test to see whether they followed a normal distribution. Differences in the mean values of each variable for each tooth were compared and statistically analyzed using a paired student t-test (statistically significant at $p < 0.05$). The relationship between the measurements obtained by the two different methods was evaluated using the Pearson correlation coefficient and regression line analysis. To confirm that both methods are comparable, the correlation coefficient (r) must be high, and the confidence intervals of the slope and intercept must contain 1 and 0, respectively. The coefficient of determination ($R^2$) was calculated in order to determine the percent variation in virtual cervical measurements accounted for by the physical cervical measurements. Discrepancy between methods was calculated as the differences between the mean value of each measurement determined by each method, compared to the mean value of the measurement collected by the physical method and expressed as a percentage.

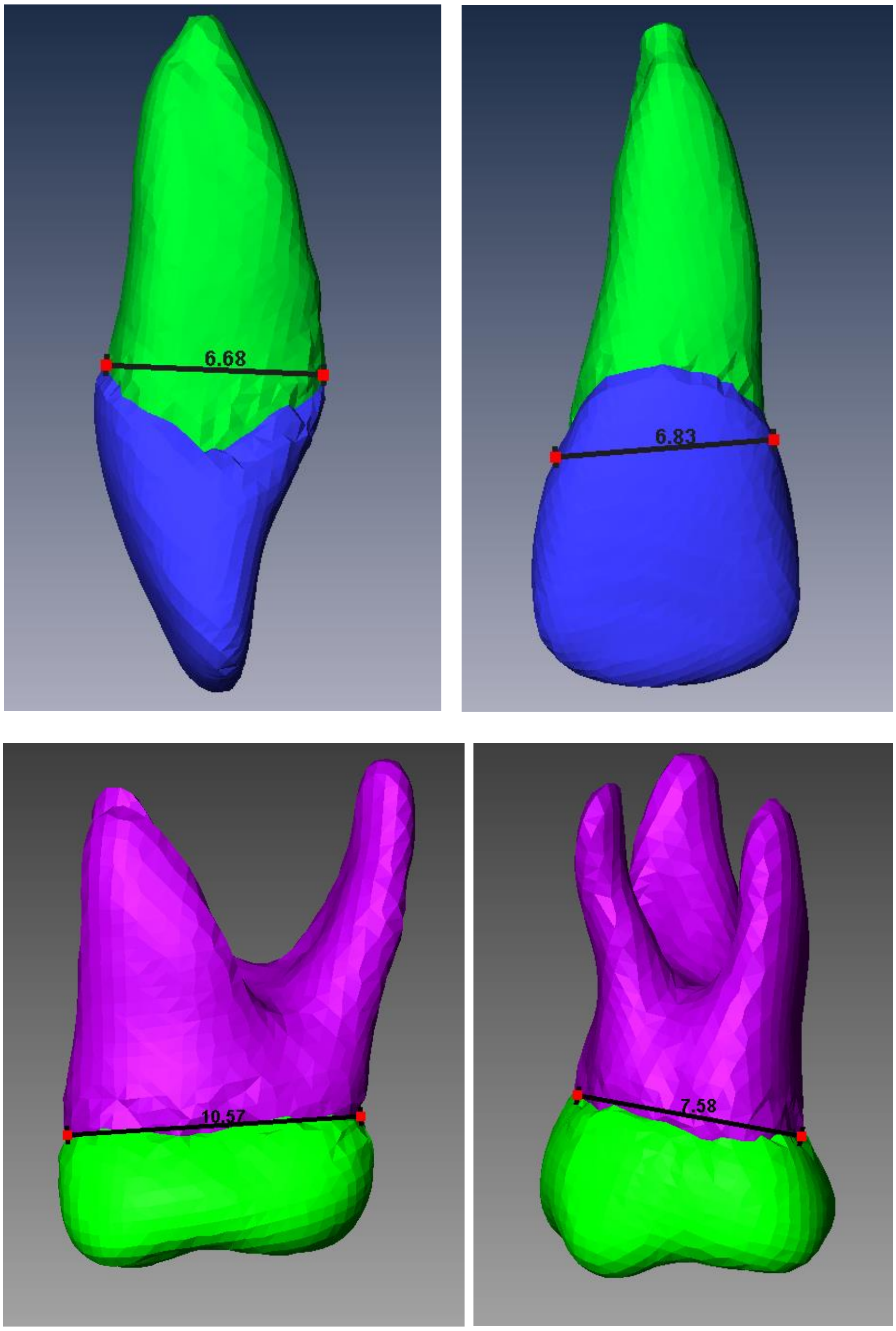


**Fig. 1.** Cervical buccolingual (left) and mesiodistal (right) measurements on maxillary first incisor and maxillary first molar. Crowns and roots were color-coded to facilitate differentiation.

## RESULTS

The Kolmogorov-Smirnov test showed that the measurements all had a normal distribution. Intra- and inter-observer TEM, rTEM, and the coefficient of reliability (R) for physical and virtual cervical measurements are provided in Table 1. Intra-observer error was low and inter-observer error was slightly higher for both methods. TEM values for both cervical measurements varied from 0.03 to 0.05mm. The mean rTEM was 0.62% for physical cervical measurements, and 0.60% for virtual cervical measurements, with R values > 0.99 for all measurements (Table 1). The rTEM and R values for all the measurements were below the 5% rTEM and above the 0.95 R standards for anthropometric studies (Franklin et al., 2013).

Table 2 shows the mean cervical mesiodistal and buccolingual sizes of each of the teeth, for both arches, and standard deviations for both methods. No significant differences were observed between the two methods ($p > 0.05$), except for the mesiodistal measurement of the mandibular second molar and the buccolingual measurement of the maxillary second molar ($p < 0.05$). The highest level of significance (> 0.90) was observed in mesiodistal measurements of the maxillary first incisor, and buccolingual measurements of the maxillary and mandibular third premolars. In general, when compared to cervical buccolingual measurements, cervical mesiodistal measurements showed a higher level of significance, similar to that found in mandibular teeth, when compared to maxillary teeth. Maxillary and mandibular third premolars were the only teeth which provided a very high level of significance (> 0.70) for both cervical mesiodistal and buccolingual measurements (Table 2). On average, virtual cervical mesiodistal measurements were 0.02mm smaller than physical cervical mesiodistal measurements, while virtual cervical buccolingual measurements were 0.01mm smaller than physical cervical buccolingual measurements (Table 2). As Table 2 shows, the discrepancy between both methods was lower than 1%.

**Table 1.** TEM, rTEM, and coefficient of reliability results evaluating inter-observer error in 2D and 3D cervical measurements

| | N | 2D cervical | | | | | | 3D cervical | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Intra-observer error | | | Inter-observer error | | | Intra-observer error | | | Inter-observer error | | |
| **MD** | | **TEM** | **rTEM** | **R** | **TEM** | **rTEM** | **R** | **TEM** | **rTEM** | **R** | **TEM** | **rTEM** | **R** |
| UI1 | 19 | 0.03 | 0.45 | 1 | 0.04 | 0.57 | 1 | 0.04 | 0.61 | 1 | 0.03 | 0.46 | 1 |
| LI1 | 21 | 0.02 | 0.58 | 0.99 | 0.03 | 0.75 | 0.98 | 0.03 | 0.9 | 0.98 | 0.02 | 0.7 | 0.99 |
| UI2 | 20 | 0.03 | 0.61 | 1 | 0.05 | 0.75 | 1 | 0.04 | 0.78 | 1 | 0.03 | 0.56 | 1 |
| LI2 | 20 | 0.04 | 0.78 | 0.99 | 0.03 | 0.87 | 0.99 | 0.03 | 0.88 | 0.99 | 0.03 | 0.76 | 0.99 |
| UC | 24 | 0.03 | 0.53 | 1 | 0.04 | 0.68 | 1 | 0.04 | 0.77 | 1 | 0.03 | 0.6 | 1 |
| LC | 23 | 0.03 | 0.49 | 1 | 0.04 | 0.69 | 1 | 0.03 | 0.59 | 1 | 0.02 | 0.44 | 1 |
| UP3 | 24 | 0.04 | 0.72 | 0.99 | 0.04 | 0.76 | 1 | 0.04 | 0.8 | 0.99 | 0.03 | 0.6 | 1 |
| LP3 | 22 | 0.03 | 0.55 | 0.99 | 0.03 | 0.76 | 0.99 | 0.04 | 0.79 | 0.99 | 0.03 | 0.62 | 1 |
| UP4 | 22 | 0.03 | 0.65 | 1 | 0.04 | 0.75 | 0.99 | 0.04 | 0.81 | 0.99 | 0.03 | 0.57 | 1 |
| LP4 | 23 | 0.04 | 0.47 | 1 | 0.04 | 0.83 | 0.99 | 0.04 | 0.77 | 0.99 | 0.02 | 0.5 | 1 |
| UM1 | 24 | 0.04 | 0.39 | 1 | 0.05 | 0.56 | 0.99 | 0.04 | 0.5 | 0.99 | 0.03 | 0.38 | 1 |
| LM1 | 23 | 0.03 | 0.26 | 1 | 0.04 | 0.52 | 1 | 0.04 | 0.44 | 1 | 0.03 | 0.32 | 1 |
| UM2 | 24 | 0.04 | 0.45 | 1 | 0.05 | 0.62 | 0.99 | 0.03 | 0.46 | 1 | 0.03 | 0.38 | 1 |
| LM2 | 24 | 0.03 | 0.36 | 1 | 0.05 | 0.57 | 0.99 | 0.04 | 0.43 | 1 | 0.03 | 0.37 | 1 |
| UM3 | 8 | 0.04 | 0.54 | 1 | 0.04 | 0.61 | 1 | 0.04 | 0.7 | 1 | 0.03 | 0.39 | 1 |
| LM3 | 13 | 0.03 | 0.36 | 1 | 0.05 | 0.54 | 1 | 0.05 | 0.51 | 1 | 0.03 | 0.29 | 1 |
| **BL** | | | | | | | | | | | | | |
| UI1 | 19 | 0.03 | 0.48 | 1 | 0.04 | 0.58 | 1 | 0.04 | 0.61 | 0.99 | 0.03 | 0.46 | 1 |
| LI1 | 21 | 0.03 | 0.49 | 0.99 | 0.04 | 0.68 | 0.99 | 0.04 | 0.66 | 0.99 | 0.03 | 0.58 | 0.99 |
| UI2 | 20 | 0.02 | 0.44 | 1 | 0.03 | 0.61 | 1 | 0.04 | 0.75 | 0.99 | 0.03 | 0.6 | 0.99 |
| LI2 | 20 | 0.03 | 0.47 | 0.99 | 0.04 | 0.65 | 0.99 | 0.03 | 0.6 | 0.99 | 0.02 | 0.43 | 1 |
| UC | 24 | 0.03 | 0.33 | 1 | 0.04 | 0.49 | 1 | 0.03 | 0.45 | 0.99 | 0.03 | 0.35 | 1 |
| LC | 23 | 0.02 | 0.31 | 1 | 0.03 | 0.44 | 1 | 0.04 | 0.62 | 1 | 0.03 | 0.45 | 1 |
| UP3 | 24 | 0.03 | 0.38 | 1 | 0.04 | 0.56 | 0.99 | 0.04 | 0.49 | 1 | 0.03 | 0.41 | 1 |
| LP3 | 22 | 0.03 | 0.45 | 0.99 | 0.04 | 0.69 | 0.99 | 0.04 | 0.54 | 1 | 0.03 | 0.42 | 1 |
| UP4 | 22 | 0.03 | 0.39 | 1 | 0.04 | 0.55 | 1 | 0.04 | 0.5 | 1 | 0.03 | 0.37 | 1 |
| LP4 | 23 | 0.03 | 0.35 | 1 | 0.05 | 0.71 | 1 | 0.03 | 0.5 | 1 | 0.04 | 0.56 | 1 |
| UM1 | 24 | 0.03 | 0.29 | 1 | 0.04 | 0.46 | 0.99 | 0.03 | 0.34 | 1 | 0.03 | 0.28 | 1 |
| LM1 | 23 | 0.03 | 0.33 | 1 | 0.04 | 0.53 | 1 | 0.03 | 0.4 | 1 | 0.03 | 0.3 | 1 |
| UM2 | 24 | 0.03 | 0.32 | 1 | 0.04 | 0.52 | 1 | 0.04 | 0.36 | 1 | 0.03 | 0.29 | 1 |
| LM2 | 24 | 0.03 | 0.38 | 1 | 0.04 | 0.49 | 1 | 0.05 | 0.62 | 0.99 | 0.04 | 0.51 | 0.99 |
| UM3 | 8 | 0.03 | 0.36 | 1 | 0.04 | 0.62 | 1 | 0.04 | 0.44 | 1 | 0.03 | 0.32 | 1 |
| LM3 | 13 | 0.03 | 0.39 | 1 | 0.04 | 0.48 | 1 | 0.04 | 0.57 | 0.99 | 0.03 | 0.33 | 1 |

MD= Mesiodistal, BL= Buccolingual, U = Upper, L = Lower, I = Incisor, C = Canine, P = Premolar, M = Molar

**Table 2.** Paired student t-test, mean difference, and discrepancy percentages comparing the means between 2D and 3D cervical measurements.

| | N | 2D cervical | | 3D cervical | | Mean difference | *t*-value | *p*-value | Discrepancy% |
|---|---|---|---|---|---|---|---|---|---|
| **MD** | | **Mean** | **SD** | **Mean** | **SD** | | | | |
| UI1 | 31 | 6.28 | 0.51 | 6.28 | 0.58 | 0.00 | 0.03 | 0.98 | 0.00 |
| LI1 | 33 | 3.49 | 0.23 | 3.49 | 0.23 | 0.00 | -0.19 | 0.84 | 0.00 |
| UI2 | 30 | 4.68 | 0.50 | 4.64 | 0.55 | 0.04 | 1.97 | 0.06 | 0.85 |
| LI2 | 34 | 3.85 | 0.35 | 3.83 | 0.38 | 0.02 | 1.03 | 0.31 | 0.52 |
| UC | 33 | 5.45 | 0.51 | 5.44 | 0.52 | 0.01 | 0.53 | 0.60 | 0.18 |
| LC | 39 | 5.20 | 0.56 | 5.19 | 0.56 | 0.01 | 0.81 | 0.43 | 0.19 |
| UP3 | 30 | 4.58 | 0.43 | 4.60 | 0.43 | -0.02 | -0.95 | 0.35 | -0.44 |
| LP3 | 34 | 4.73 | 0.37 | 4.73 | 0.42 | 0.00 | -0.22 | 0.83 | 0.00 |
| UP4 | 40 | 4.61 | 0.36 | 4.57 | 0.36 | 0.04 | 2.00 | 0.06 | 0.87 |
| LP4 | 32 | 4.95 | 0.44 | 4.93 | 0.47 | 0.02 | 0.94 | 0.36 | 0.40 |
| UM1 | 35 | 7.76 | 0.42 | 7.77 | 0.41 | -0.01 | -0.32 | 0.75 | -0.13 |
| LM1 | 40 | 8.89 | 0.51 | 8.87 | 0.52 | 0.02 | 0.71 | 0.48 | 0.22 |
| UM2 | 40 | 7.63 | 0.61 | 7.63 | 0.66 | 0.00 | 0.19 | 0.85 | 0.00 |
| LM2 | 35 | 8.88 | 0.62 | 8.80 | 0.62 | 0.08 | 2.24 | 0.03* | 0.56 |
| UM3 | 14 | 6.88 | 0.85 | 6.85 | 0.83 | 0.03 | 1.51 | 0.16 | 0.44 |
| LM3 | 30 | 9.00 | 0.77 | 8.97 | 0.74 | 0.03 | 1.53 | 0.14 | 0.33 |
| **BL** | | | | | | | | | |
| UI1 | 31 | 6.27 | 0.40 | 6.25 | 0.48 | 0.02 | 1.10 | 0.23 | 0.32 |
| LI1 | 33 | 5.38 | 0.33 | 5.36 | 0.36 | 0.02 | 0.79 | 0.44 | 0.37 |
| UI2 | 30 | 5.58 | 0.47 | 5.54 | 0.43 | 0.04 | 1.45 | 0.16 | 0.72 |
| LI2 | 34 | 5.83 | 0.36 | 5.78 | 0.34 | 0.05 | 1.99 | 0.06 | 0.86 |
| UC | 33 | 7.58 | 0.63 | 7.54 | 0.66 | 0.04 | 1.68 | 0.10 | 0.53 |
| LC | 39 | 7.28 | 0.74 | 7.22 | 0.72 | 0.06 | 2.42 | 0.20 | 0.82 |
| UP3 | 30 | 7.91 | 0.68 | 7.91 | 0.64 | 0.00 | -0.11 | 0.91 | 0.00 |
| LP3 | 34 | 6.58 | 0.48 | 6.57 | 0.46 | 0.01 | 0.13 | 0.90 | 0.15 |
| UP4 | 40 | 7.95 | 0.75 | 7.92 | 0.74 | 0.03 | 1.25 | 0.22 | 0.38 |
| LP4 | 32 | 7.15 | 0.55 | 7.1 | 0.55 | 0.05 | 1.81 | 0.08 | 0.70 |
| UM1 | 35 | 9.75 | 0.63 | 9.79 | 0.58 | -0.04 | -1.38 | 0.18 | -0.41 |
| LM1 | 40 | 8.62 | 0.52 | 8.63 | 0.51 | -0.01 | -0.80 | 0.44 | -0.12 |
| UM2 | 40 | 9.90 | 0.76 | 9.99 | 0.77 | -0.09 | -3.07 | 0.00* | -0.71 |
| LM2 | 35 | 8.19 | 0.60 | 8.22 | 0.59 | -0.03 | -1.40 | 0.17 | -0.37 |
| UM3 | 14 | 9.16 | 0.86 | 9.12 | 0.83 | 0.04 | 1.11 | 0.23 | 0.44 |
| LM3 | 30 | 7.96 | 0.51 | 7.95 | 0.45 | 0.01 | 0.24 | 0.81 | 0.13 |

SD: Standard deviation, MD= Mesiodistal, BL= Buccolingual, U= Upper, L= Lower, I= Incisor, C= Canine, P= Premolar, M= Molar.
$^*p < 0.05$

Table 3 shows the correlation coefficient and the *p* values (< 0.01) for mesiodistal and buccolingual measurements of each tooth. All the measurements showed a very high positive correlation between physical and virtual measurements, with a correlation coefficient greater than 0.92. The weakest correlation (= 0.92) was observed between the physical mesiodistal and buccolingual measurements of the mandibular first incisor and its virtual measurement, and also between the physical buccolingual measurement of the mandibular second incisor and its virtual measurement. The strongest correlation (= 0.99) was observed in seven of the measurements (Table 3).

**Table 3.** Matrix of Pearson correlation coefficient between 2D cervical and 3D cervical measurements for each tooth.

| **Tooth** | | **Original sample** | | | |
|---|---|---|---|---|---|
| | **N** | **Coefficient** | | ***p-value**** | |
| | | **MD** | **BL** | **MD** | **BL** |
| UI1 | 31 | 0.97 | 0.98 | 0.00 | 0.00 |
| LI1 | 33 | 0.92 | 0.92 | 0.00 | 0.00 |
| UI2 | 30 | 0.94 | 0.96 | 0.00 | 0.00 |
| LI2 | 34 | 0.96 | 0.92 | 0.00 | 0.00 |
| UC | 33 | 0.98 | 0.98 | 0.00 | 0.00 |
| LC | 39 | 0.96 | 0.98 | 0.00 | 0.00 |
| UP3 | 30 | 0.96 | 0.99 | 0.00 | 0.00 |
| LP3 | 34 | 0.95 | 0.96 | 0.00 | 0.00 |
| UP4 | 40 | 0.95 | 0.99 | 0.00 | 0.00 |
| LP4 | 32 | 0.95 | 0.97 | 0.00 | 0.00 |
| UM1 | 35 | 0.96 | 0.98 | 0.00 | 0.00 |
| LM1 | 40 | 0.96 | 0.98 | 0.00 | 0.00 |
| UM2 | 40 | 0.99 | 0.99 | 0.00 | 0.00 |
| LM2 | 35 | 0.98 | 0.98 | 0.00 | 0.00 |
| UM3 | 14 | 0.99 | 0.99 | 0.00 | 0.00 |
| LM3 | 30 | 0.99 | 0.98 | 0.00 | 0.00 |

MD= Mesiodistal, BL= Buccolingual, U = Upper, L = Lower, I = Incisor, C = Canine, P = Premolar, M = Molar.
* Correlation is significant at $p < 0.01$ for all measurements.

The slopes, intercepts, and associated 95% confidence intervals derived from linear regression on the mesiodistal and buccolingual measurements from the two methods are presented in Table 4. The 95% confidence interval levels of the regression line slopes include 1 in all cases, and the intercepts include 0, indicating that there are no significant differences between the methods. The coefficient determination values also showed that 98-100% of the virtual mesiodistal and buccolingual measurements could be predicted from the physical measurements (Table 4).

**Table 4.** Slope and intercept, 95 percent confidence intervals (95% CI), Pearson correlation coefficient, and the coefficient of determination ($R^2$) between 2D cervical and 3D cervical measurements for all teeth.

| | **Slope (95% CI)** | **Intercept (95% CI)** | **Correlation coefficient (R)** | ***p*-value*** | **Coefficient of determination ($R^2$)** |
|---|---|---|---|---|---|
| UMD | 1.00 (1.00-1.02) | -0.07 (-0.15- 0.00) | 1.00 | 0.00 | 0.99 |
| UBL | 1.00 (0.99-1.02) | -0.04 (-0.13- 0.06) | 1.00 | 0.00 | 0.99 |
| LMD | 1.00 (0.99-1.00) | 0.02 (-0.03- 0.07) | 1.00 | 0.00 | 1.00 |
| LBL | 1.00 (0.99-1.02) | -0.05 (-0.17- 0.08) | 0.99 | 0.00 | 0.98 |
| All MD | 1.00 (0.99-1.00) | 0.00 (-0.04- 0.04) | 1.00 | 0.00 | 1.00 |
| All BL | 1.00 (1.00-1.02) | -0.08 (-0.15- -0.01) | 1.00 | 0.00 | 0.99 |

MD= Mesiodistal, BL= Buccolingual, U = Upper, L = Lower, I = Incisor, C = Canine, P = Premolar, M = Molar.
*Correlation is significant at $p < 0.01$ for all measurements.

## DISCUSSION

To the our knowledge, this study is the first attempt at comparison between physical and virtual cervical mesiodistal and buccolingual measurements, which have recently become common in odontometric sex estimation studies. Our results showed that there were no differences between methods; even the few statistically significant differences did not reach 1%. Maximum and minimum differences between physical and virtual measurements were 0.09 and 0.00 mm, respectively, lower than those reported by other studies (Lu et al., 2000; Smith et al., 2009). Pearson correlation and regression line analysis confirmed that there was a high positive correlation between the two methods, and that virtual cervical measurements could easily be predicted based on physical measurements. These findings agree with those of previous studies (Kim et al., 2007; Tarazona et al., 2013).

In this study each tooth was segmented from the jaw using the thresholding tool in the AMIRA software. This enables the user to create a separate virtual model of every tooth, regardless of its situation (loose/in situ). In virtual analysis, all in situ teeth become loose teeth; this differs from physical cervical measurements where in situ teeth cannot be rotated or removed from the jaw. To increase the reliability and ease of the CEJ identification process in virtual analysis, the crown was separated from the root using a second threshold level, and crown and root of the same tooth were color-coded. In doing so, the researcher and the second observer responsible for inter-observer error analysis found the process of CEJ line identification using virtual methods easier and more accurate. Furthermore, the ability to make a separate virtual model of each in-situ tooth enables the user to take measurements from different aspects. The measurement differences caused by taking the mesiodistal measurement from a different position (buccal or lingual) in physical cervical measurements was not observed in use of the virtual method.

Intra- and inter-observer error results confirmed that virtual imaging was as reliable and accurate as the physical system for measuring teeth. Previous studies have reported similar findings for measurements obtained using virtual methods or direct measurement on plaster models (Smith et al., 2009; El-Zanaty et al., 2010; Ashar et al., 2012). However, these studies are in crown mesiodistal and buccolingual measurements, rather than cervical. In the current study, both physical and virtual measurements generally provided excellent reliability within and between observers. The buccolingual dimension was measured most reliably, whether based on virtual or physical measurements, whereas mesiodistal measurements displayed lower reliability. However, virtual mesiodistal measurements showed slightly better consistency and reliability compared to physical cervical measurements, which could be due to better identification of the CEJ line in virtual analysis.

In conclusion, these findings show that dental cervical measurements can be obtained using physical or virtual methods. Comparison of the two methods highlights the effectiveness and significance of virtual analysis in this field of study, and enables researchers to confidently move from physical teeth to virtual models. This study confirms a strong correlation and linear relationship between actual measurements obtained using Hillson-Fitzgerald dental calipers and the measurements taken on virtual models with AMIRA software. It must be stressed that the comparisons in this study are based on models of teeth derived from a specific CT scanning protocol. The positive results of this study are encouraging for the reliability of virtual measurements from medical CT scan-derived models but this should not be considered a fact for other scanning conditions without further testing.

## ACKNOWLEDGMENTS

We would like to thank Dr Thomas Schoenemann and Dr Janet Monge for making CT scans available through the Open Research Scan Archive at the UP Museum of Archaeology and Anthropology. We would also like to thank Dr Linda Fibiger for her valuable contribution and support during the examination process and Dr Ali Haghighi for participating in the inter-observer error study.

**References:**

Ashar, A., Hughes, T., James, H., Kaidonis, J., Khamis, F. & Townsend, F. (2012) Dental crown and arch size in European and Australian Aboriginals. In: G. Townsend., E. Kanazawa, & H. Takayama (Ed.), *New direction in dental anthropology* (pp. 65-80). Adelaide: The University of Adelaide.

Dyson, Jr., R.H. (1983) Introduction: The genesis of the Hasanlu project. In: M.M. Voigt (Ed.), *Hajji Firuz Tepe, Iran: The Neolithic settlement* (pp. xxv-xxviii). Philadelphia: UPM.

El-Zanaty, H.M., El-Beialy, A.R., Abou El-Ezz, A.M., Attia, KH., El-Bialy, A.R. and Mostafa, Y.A. (2010) Three-dimentional dental measurements: An alternative to plaster models. *American Journal of Orthodontics and Dentofacial Orthopedics*, 137, 259-265.

Franklin, D., Cardini, A., Flavel, A., Kuliukas, A., Marks, M.K. & Hart, R, et al. (2013) Concordance of traditional osteometric and volume-rendered MSCT interlandmark cranial measurements. *International Journal of Legal Medicine,* 127, 505–520.

Hillson, S., FitzGerald, C. & Flinn, H. (2005) Alternative dental measurements: Proposals and relationships with other measurements. *American Journal of Physical Anthropology,* 126, 413-426.

Hunter, W.S. & Priest, W.R. (1960) Errors and discrepancies in measurement of tooth size. *Journal of Dental Research*, 39, 405-414.

Kazzazi, S.M., & Kranioti, E.F. (2016). Sex estimation using cervical dental measurements in an archaeological population from Iran. *Archaeological and Anthropological Sciences,* doi:10.1007/s12520-016-0363-7.

Kim, I, Paik, K.S. & Lee, S.P. (2007) Quantitative evaluation of the accuracy of micro-computed tomography in tooth measurement. *Clinical Anatomy,* 20, 27-34.

Liu, Y., Olszewski, R., Alexandroni, E.S., Enciso, R., Xu, T. & Mah, J.K. (2010) The validity of in vivo tooth volume determination from con-beam computed tomography. *The Angle Orthodontist*, 80, 160-166.

Lu, P., Li, Z., Wang, Y., Chen, J. & Zhao, J. (2000) The research and development of non-contact 3-D laser dental model measuring and analyzing system. *Chinese Journal of Dental Research*, 3, 7–14.

McKeown, H.F., Robinson, D.L., Elcock, C., Al-Sharood, M. & Brook, A.H. (2002) Tooth dimensions in hypodontia patients, their unaffected relatives and a control group measured by a new image analysis system. *European Journal of Orthodontics,* 24, 131-141.

Monge, J. & McCarthy, C. (2011) A life of violence: When warfare and interpersonal violence intertwine at Hasanlu, period IVB. In: M. Schauensee (Ed.), *Peoples and crafts in period IVB at Hasanlu, Iran* (pp. 183-193). Philadelphia: UPM.

Moorrees, C.F.A., Thomsen, S.O., Jensen, E. & Yen, P.K. (1957) Mesiodistal crown diameters of the deciduous and permanent teeth in individuals. *Journal of Dental Research,* 36, 39-47.

Richardson, E.R. & Malhotra, S.K. (1975) Mesiodistal crown dimension of the permanent dentition of American Negroes. *American Journal of Orthodontics,* 68, 157-164.

Smith, R., Zaitoun, H., Coxon, T., Karmo, M., Kaur, G., Townsend, G., & Brook, A. (2009). Defining new dental phenotypes using 3D image analysis to enhance discrimination and insights into biological processes. *Archives of Oral Biology,* 54, S118-S125.

Spoor, F., Leakey, M.G. & Leakey, L.N. (2010) Hominin diversity in the middle Pliocene of Eastern Africa: The maxilla of KNM-WT 40000. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 365, 3377-3388.

Tarazona, B., Liamas, J.M., Cibrian, R., Gandia, J.L. & Paredes, V. (2013). A comparison between dental measurements taken from CBCT models and those taken from a Digital Method. *European Journal of Orthodontics,* 35, 1-6.

Ulijaszek, S.J. & Kerr, D.A. (1999) Anthropometric measurement error and the assessment of nutritional status. *British Journal of Nutrition*, 82, 165-177.

Viciano, J., D'Anastasio, R. & Capasso, L. (2015) Odontometric sex estimation on three populations of the Iron Age from Abruzzo region (Central-Southern Italy). *Archives of Oral Biology*, 60, 100-115.